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THE ATOM

By

Professor E. N. da C. ANDRADE, D.Sc., Ph.D.

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WHO LIKES TO TALK ABOUT THESE THINGS

CONTENTS

THE ATOM

CHAPTER I

THE ATOMIC THEORY

From the time when serious thinking about ourselves and our surroundings began, the question has been asked as to what matter is made of. In particular, the following problem has been discussed: Suppose we could take a piece of some substance, say copper, and magnify it indefinitely, should we see in the end that it was made up of particles with spaces between them, held together by certain attractive forces, or should we find that, no matter how much larger we made it appear, it was as continuous throughout as it appeared when unmagnified? To take a homely simile, would it appear like a bushel of peas, or like a jelly? Another way of asking this question is to demand whether, supposing our senses were fine enough and our instruments delicate enough, we could go on dividing up a piece of matter, say, copper, into smaller and smaller fragments indefinitely, or whether we should at last come to a fragment which could not be further divided, at any rate without its ceasing to be copper. On the bushel of peas theory, we should come to an end when we had isolated a single pea, while we could go on chopping our little bit of jelly smaller and smaller without coming to a recognisable ultimate part.

The atomic theory is the bushel of peas theory. It assumes that all matter is ultimately made up of little grains which are called atoms because they cannot be further divided. For the word "atom" is derived from a Greek word meaning "that which cannot be cut."

Until within the last twenty or thirty years it was believed that an atom could not be damaged in the slightest, but we know now that we can chip little bits off atoms. The exact meaning of this will be discussed later on in the book: it is not of importance for our present purpose. If, changing our metaphor, we call atoms the bricks out of which pieces of matter—of copper, quicksilver, carbon, and suchlike—are built, they are no less our ultimate bricks because we can, by certain methods, chip little pieces from them. We cannot cut them in half, and have two half-bricks.

The question at once arises as to how many different kinds of atoms we must assume. We are acquainted with hundreds of thousands of different kinds of substances: with different metals, different woods, different stones; with the parts of living organisms, such as bones and flesh; with the enormous variety of different chemical substances which play so large a part in our life and industry, and, in contrast, with ill-defined messes, such as mud, and the products of the average cook. Are we to assume that to each substance corresponds a different atom: that the ultimate constituent of copper is a little atom of copper, the ultimate constituent of bone a little atom of bone, and the ultimate constituent of mud a little atom of mud? The last would clearly be absurd, for we know that mud is made by mixing various things; for instance, water, clay, and the little particle of wood, stone, cloth, and what not which we call dust, so that in any case it will be sufficient to discuss the ultimate parts of these things which are mixed. Suppose, then, we confine ourselves for the moment to definite chemical substances, such as copper and quicksilver, salt and sugar, water and alcohol, and inquire about their ultimate structures. Are they simple things, each with its own kind of atom, or can they be built up of other substances?

The answer, provided by the science of chemistry, is that certain substances are simple, and cannot by chemical means be built up of other substances, but that the vast

majority of substances are compounds, which can be made in the laboratory (if not in the laboratory of flasks and test tubes, then in the wonderfully equipped laboratory which is constituted by any living substance) from the simple substances. Thus the solids, copper, sulphur, carbon; the liquids, quicksilver, and bromine; the gases, oxygen, nitrogen, and hydrogen, are examples of simple substances, which cannot be manufactured by making substances combine. Such substances are called elements.* Some ninety elements, in the sense just defined, are known. Familiar substances which are elements are the pure metals (as distinct from alloys), such as aluminium, iron, cobalt, nickel, zinc, platinum; the non-metallic solids, carbon, arsenic, iodine, and phosphorus; and the liquids and gases just mentioned. Some of these elements occur much more commonly than others; thus the eight elements, oxygen, silicon, aluminium, iron, calcium, magnesium, sodium and potassium make up nearly ninety-nine-hundredths by weight of the earth's crust, while the fifty least common elements, which include many useful metals, all together constitute only about one ten-thousandth of the earth's crust. It will come as a surprise to many that oxygen is the commonest element, not, of course, as a gas, but because it is combined in important proportions by weight in nearly all common substances.

From these elements all known substances are built up, just as from a few types of girders, beams, plates, and so on, the steel work of all structures, bridges of various sizes and shapes, towers, and suchlike can be made. Thus ordinary kitchen salt is a compound of the soft metal sodium and the gas chlorine, while sugar is composed of carbon, oxygen, and hydrogen. Marble is composed of calcium, carbon, and oxygen; hydrogen

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* The use of the word element to denote the four supposedly, but not actually, simple substances earth, air, fire, and water, is a relic of ancient Greek belief, and has no place in modern science.

peroxide, by which blondes are manufactured, of oxygen and hydrogen. These substances will serve to illustrate a few of the facts of chemistry which we require for our discussion. In the first place we see that when elements combine, the obvious properties of the compound have nothing to do with the properties of the elements from which it is made. Sodium is a soft substance, which can be cut with a knife, leaving a metallic surface which tarnishes at once in air; if thrown into water, it floats, and decomposes the water so vigorously that, in certain circumstances, combustion and explosions may ensue. Chlorine is poisonous to breathe; in fact, it was the first gas to be used as poison gas in the Great War. Yet chlorine combines readily with sodium to form ordinary salt, which is wholesome, and dissolves in water without fuss. When marble is acted upon by acid, the carbon and part of the oxygen are given off, combined together to form the familiar gas carbon dioxide, used to aerate drinks. Carbon—or coke—and the two gases, hydrogen and oxygen, combined in due proportions, form sugar; combined in other proportions, they form starch. Oxygen and hydrogen combined in certain proportions form water; in other proportions, hydrogen peroxide. We see, therefore, that in a compound the properties of the combining substances are completely hidden; the substance resulting from a chemical reaction between different substances does not show a kind of average of their qualities, but has its own distinct individuality. In the second place, substances combine in perfectly definite proportions by weight to form a given substance; they are not mixed, like the ingredients of a pudding, where a little more or less of any one component may be allowed without altering the result, but put together in a precise way like a machine, where an exact number of component parts are required. In the third place, the same elements can combine in different proportions, forming quite different substances; but when they do so, the proportions by weight of the elements in the different compounds bear quite

simple relations to one another. For instance, in hydrogen peroxide, there is exactly twice as much oxygen combined with a given weight of hydrogen as there is in water; the weight of oxygen combined with a given weight of lead in pure red lead (plumbers' red lead is usually a mixture) is four as against six in the brown lead peroxide formed on the positive plate of an accumulator, and three in the oxide of lead known as litharge. These are particularly simple examples, but the laws just indicated are quite general.

Now on the atomic theory these laws are simply explained in the following way. Chemical compounds are formed by the atoms of different elements entering into combination with one another. For simplicity we will consider for the moment compounds formed of two different elements only, such as common salt. In such compounds quite a few atoms—perhaps one, and seldom more than six—of an element combine with quite a few atoms of another element to form the smallest particle which can have the properties of the substance in question. Such a particle is called a molecule: for an elementary substance the atom and the molecule may be the same thing. In the case of common salt, one atom of sodium combines with one atom of chlorine to form one molecule of salt, which is called in chemical language sodium chloride. In the case of carbon and oxygen, one atom of carbon combines with one atom of oxygen to form one molecule of carbon monoxide, which is a highly poisonous gas, formed by incomplete combustion: a favourite French method of committing suicide with a charcoal brazier in a closed room depends upon the production of this gas, one part of which to a thousand parts of air is fatal. One atom of carbon can also combine with two atoms of oxygen to form carbon dioxide. The weight of oxygen combined with an ounce of carbon is twice as great in carbon dioxide as in carbon monoxide. Iron forms two compounds with chlorine, in which the weights of chlorine combined with a given weight of iron are as two to three: in the one compound one atom

of iron is combined with the two atoms of chlorine; in the other compound, one atom of iron is combined with three atoms of chlorine. This conception of atoms combining explains why in true chemical compounds the proportions are always fixed, since every ultimate part of the compound consists of a perfectly definite small number of one kind of atom combined with a perfectly definite small number of another kind of atom; it also explains why, when the same two elements combine to form different compounds, the amount of the one element combined with a fixed amount of the other element, while different in the different compounds, is always a very small multiple of a fixed amount.

To make this quite clear, let us consider a business office which buys envelopes at a fixed rate, and franks all its letters with stamps of the same denomination, and let us further imagine that it has different departments for dealing with correspondence requiring different postage. Thus, one department sends out printed leaflets requiring a single stamp on the envelope; another department sends out cards, requiring two stamps; another department letters requiring three stamps; another department foreign letters requiring five stamps. In a given department the ratio of the amount spent on envelopes to the amount spent on stamps will always be the same; in another department it will be different, but the amount spent on stamps per envelope will be a simple multiple of that prevailing in the first department. Anybody investigating the books of the business would come to the conclusion that the costs would be most simply explained by supposing that a single envelope combined with a single stamp in one department, and with two, three, or more stamps in other departments. Substitute weights for costs, and compounds for departments, and we have the chemical facts.

The importance of the atomic theory in chemistry is that it enables us to form a picture of what is going on when chemical combination takes place, and to anticipate what we must do to form a given molecule. It is not

too much to say that without this scheme of combining atoms, and atoms taking the place of others in a molecule, we should have none of the synthetic dye-stuffs that we possess to-day. By means of the atomic theory, we can write down exactly what quantities of substances are required to take part in a given reaction, and can foretell what steps must be taken when it is desired to form one compound from another. The atomic theory is to chemistry what bookkeeping and accountancy are to business. We might carry on somehow without it, but we should have no control of our knowledge, no systematic record of our achievements to which we could refer, no reasoned lines for planning future campaigns.

We now turn to the application of the atomic theory to certain general aspects of the nature of matter, and in particular to the nature of heat. Matter as we know it can exist in three forms, as a solid, a liquid, or a gas, and a given substance can take on one or the other form, according to the temperature and pressure. Thus, to take the familiar example of water, it is a solid, ice, when very cold; a liquid, under ordinary conditions; and an invisible gas, steam, when very hot, the temperature at which it turns into steam depending on the pressure, as every engineer knows. We say that steam is an invisible gas, for what is ordinarily called steam is minute drops of hot water, formed by the steam condensing in the cold air: close to the spout of a kettle there is a space where the issuing steam cannot be seen. A somewhat less familiar example of the three states is the gas, carbon dioxide, used for making aerated drinks, which has already been mentioned. This is sold in steel cylinders, in which it exists under great pressure as a liquid. When it is let out slowly with the tap end of the cylinder uppermost it issues as an invisible gas, but if the cylinder be reversed and the liquid allowed to issue rapidly, intense cold is produced, and a snow-like substance is formed, which may be caught in a cloth wrapped round the nozzle. It is carbon dioxide in solid form. All substances which exist normally as gases,

including the air we breathe, can nowadays be reduced to liquid and to solid forms: liquid air can, in fact, be bought commercially, like milk. The last gas to be subdued was helium, which was not reduced to solid form until 1926. Whether a substance exists as a solid, a liquid, or a gas, does not, in fact, depend upon the substance, but upon the conditions. If the normal temperature of the world were that of an oven, we should (providing we could exist) speak of water substance as a gas, which could be liquefied and solidified by special means, and similarly, we should regard the metal tin as a liquid.

How are we to regard these different forms of matter on the atomic theory? We must first say a word as to the nature of heat. Every body is made up of atoms, bound together in little knots or molecules if the body is a compound, and not an element. These molecules are in ceaseless agitation, and so possess energy of motion. This invisible, or internal, energy, due not to the motion of the body as a whole, but to a dashing hither and thither of particles much too minute to be seen even with a microscope, constitutes heat. It is taking place in bodies at ordinary temperatures, but when we heat a body it becomes more violent, when we cool a body it becomes less marked. In a heat engine of any kind, we convert some of the invisible molecular motion into a visible motion of the piston. From this view of heat we see at once a very important fact—namely, that there must be a limit of coldness, or an absolute zero of temperature below which we cannot go. For when a body is cold enough for all molecular motion to cease we cannot go to any lower temperature: molecules cannot be any less lively than still. It can be calculated that this so-called absolute zero of temperature is 273 degrees centigrade below the melting-point of ice, and temperatures within less than one degree of this have actually been attained in the laboratory. On the other hand, there is no limit of high temperature, for however energetically the molecules may be dashing about they can always go faster.

It can be estimated that the temperature in the interior of certain stars is to be measured in millions of degrees, but it is inconceivable that anywhere can exist a temperature lower than 273 degrees centigrade below zero.

Now in matter we have a conflict between two influences. In the first place, the molecules attract one another, and so tend to settle down into a state where all the particles are bound firmly together by the forces which they exert on one another. Against this we have the movement of the molecules which constitutes heat: every one of them is in ceaseless agitation, except in the case where the temperature is near the absolute zero. The higher the temperature, the more violent the motion of the molecules. This motion tends to keep the molecules from settling down, and in this sense acts in the opposite way to the attractive forces. Whether a body exists in the solid, liquid or gaseous state depends upon the relative importance of the two effects.

In a solid the attractions prevail. The molecules occupy more or less fixed positions, depending upon the forces exerted by the other molecules, and their heat motion consists of a vibration or trembling of the molecule, which never takes it far from its fixed abode. In a liquid the attractions and the heat motions are more evenly balanced, so that, while the attractions play a considerable part, yet any molecule can work its way through the other molecules. It makes frequent collisions with them, but can slowly move by itself to a distant spot, or, if we care to stir the liquid, we can move some molecules farther away from others. In a gas at ordinary pressure, the molecules are generally sparsely scattered, the attractions are relatively unimportant, and the molecules move in straight lines over distances which are large compared to the size of a molecule, and act on one another mainly by collisions. The pressure which a gas exerts is merely the effect of a bombardment on the side of the containing vessel by millions of millions of tiny molecular projectiles, which bounce off again. In a solid and a liquid the molecules are comparatively close, and the substance

can only be compressed with difficulty: in a gas the molecules are separated by long distances, and the substance can be compressed easily.

When we heat a substance we increase the energy of the heat motion of the molecules, by communicating to them some of the energy of motion of the molecules of the heating body—flame or what not. Hence, although in the beginning the attractive forces between the molecules may be the predominating influence, as the temperature rises the heat agitation eventually becomes sufficient for the molecules to shake themselves loose from their moorings, as it were, and go cruising through the compact fleet which they constitute. The solid becomes a liquid. At a still higher temperature, the motion becomes so violent that the molecules fly off altogether from one another, and go shooting about with high velocity, the attraction only being appreciable when two molecules happen to collide, and then being insufficient to hold them together.

We can form a rough human picture of what is going on in the following way. In a solid, the molecules can be pictured as a crowd of men all doing physical exercises—" the daily dozen "—without moving from the spot where they stand. If they have taken up their positions at random, we have a so-called amorphous or non-crystalline solid, such as glass or glue: if they are neatly drawn up in rows by a drill instructor, we have a crystalline substance, such as quartz or rock-salt or washing soda. In a liquid the molecules can be pictured as a swarm of men gathered together in a hall at a crowded reception; they are tightly wedged, but each one works his way through the others, with many a push and apology, and we cannot expect the same two men to be near each other all through the evening. (If we want two kinds of atoms, we may take men and women; if dancing starts we have chemical combination, two atoms combining to form a molecule.) For a gas we have to think of a large open space on which men are walking without looking where they are going;

each man continues in a straight line until he bumps into someone else, when he abruptly starts off again in a different direction. In each case, the hotter the substance the more rapid the motion. If a cinematograph picture could be taken of the molecules of the air in a room all we should have to do to represent the air in an oven would be to run the film more quickly.

We have now obtained some idea of the outlines of modern atomic theory. A piece of copper wire appears to be continuous and inert only because of the minuteness of the molecules, just as a large and animated crowd may appear to an observer high in an aeroplane merely as a tranquil brown patch. When chemical combination takes place, what really happens is a regrouping of atoms according to certain definite laws, just as, from a mixture of people, families will segregate. We have now to inquire as to how the existence, size, and number of the atoms have been definitely established.

CHAPTER II

THE SIZE AND THE NUMBER OF ATOMS

We have discussed how the theory that all bodies consist of atoms can be used to explain the broad facts of chemical combination and of the constitution of bodies. The question now arises as to whether we cannot find out something more precise about atoms: how big they are, and how close they are in different bodies—that is, how many of them there are in a piece of matter of a given size. Science is a detective story, and nature provides us with plenty of clues, if we know how to look for them. What are the clues to the size of the atom, and how can we use them to deduce the results we require? The clues discussed in the last chapter were

very general, and it might be supposed that we had placed a wrong interpretation on them. If we can check them by more detailed evidence, we shall feel more confident that we have not been on the wrong track.

As in a detective story, the results of the investigation are often given first, to arouse the reader's interest, and the methods by which they were reached described later, we will at once state the facts of which every man of science is now convinced. Atoms are not all of the same size, but they are all of the same kind of size. If someone who had no idea of what birds or their eggs were like were to ask us the size of a bird's egg, we should not waste time going into details of the different eggs, but should answer: they are an inch, or a few inches or so, across. In the same way, we can say that atoms are a hundred-millionth of an inch or so across, the smallest atom, the hydrogen atom, having a diameter of about half a hundred-millionth of an inch. About a hundred thousand atoms placed side by side make up the thickness of a cigarette paper. This may not sound so incredibly small at first, but it means that in a little cube cut from a cigarette paper, the width and breadth and height of which are all equal to the thickness of the paper (that is, in a tiny grain of dust) there are some thousand million million atoms. This assumes that in a solid the atoms are touching, or nearly touching, which we know to be true. Many striking ways can be devised for expressing the great number of atoms in a tiny grain of matter. Thus, if a staff of a thousand men were told off to count the atoms in a single one of the little bubbles of gas which collect in the side of a glass of soda-water, and if each man could count three hundred atoms a minute, and counted twelve hours a day all the year round, the job would take a million years, or, putting the population of the world at three thousand millions, and supposing everybody to count at the rate specified, it would take four months. Or again, imagine a fine human hair magnified until it

filled a street, the sides of the hair touching the houses on either side. Then a blood corpuscle, which might be adhering to the hair if it had been plucked out, would be about the size of the top of a large round table—that is, a disc of some six or seven feet across—but an atom would only be a speck of dust a thousandth of an inch across.

This suggests the most direct way of measuring the size of the atom would be to use a very powerful microscope, and magnify up a tiny speck of matter until we could see the atoms of which it was composed. This, however, is impossible. We cannot profitably magnify more than a few thousand diameters; greater magnification can be easily produced, but any increase above the figure stated leads to no further detail. This is a consequence of the fact that light itself is a wave motion, and so has a certain structure, with the result that we cannot hope to see the size or shape of anything which is smaller than a certain size. We can illustrate this fact by a simple simile. When photographs are reproduced in newspapers, a so-called process screen is used, the result of which is that the picture is broken up into a mass of black and white dots. Now suppose we wished to see the individual threads in the coat of a man in the newspaper picture. We could magnify up the picture with a magnifying-glass or a microscope until a thing the size of a thread ought to be visible, but it would not help us. The structure of the screen is too coarse, and we should merely see a very large dot. Even if we had the original photograph, the same kind of limit would be set by the grain of the plate. The wave structure of light produces a similar kind of effect, preventing us from seeing details finer than a certain size. Not only can we not see atoms by using a microscope, but we can never hope to do so, however perfect the instrument be made. That, however, does not mean that we cannot see certain effects due to them, certain clues from which the behaviour and size of the atoms can be deduced, just as the skilled detective can

deduce all the facts of a murder without ever hoping to be, or to find, an eye-witness.

First of all, let us consider some very simple experiments which show us that the atom must be very small. If a tiny droplet of oil, whose size can be measured, be placed on the surface of perfectly clean water, it spreads out, and covers a very large surface. From the size of the surface covered the thickness of the film can be simply calculated, and, since the film must be at least one atom thick, this thickness gives us what is called an upper limit for the size of the atom, that is, a size which the diameter of the atom cannot possibly exceed, although it may, of course, be much smaller. In the most delicate experiments which have been carried out with oil films, it is difficult to see the boundary of the film, and ingenious methods have been used to determine it. One method, which has been used, is to put tiny chips of camphor on the water: on clean water the chips dart about, as anyone can confirm for himself, but on greasy water they do not. A still more sensitive method is to sprinkle very fine talc powder on the water, and then blow it. On the clean water the talc moves easily, but its movement is stopped at the edge of the oil film. In this way it has been shown that continuous oil-films, not thicker than half a ten-millionth of an inch, can be obtained, so that atoms must be smaller than this. This is a very simple clue, which tells us not to expect anything large.

More precise information is based upon the atomic theory of gases, which is generally called the kinetic theory, since it accounts for the properties of gases by the motion of the atoms. We may think of the atoms as little balls dashing hither and thither, and colliding with one another. Now liquids and gases have a property which is called viscosity, by virtue of which they require a certain force to keep them in motion: if it were not for this viscosity (or internal friction, as it is sometimes called) a stirred liquid would go on moving for ever after the stirring had stopped. Roughly speak-

ing, the more difficult it is to maintain a liquid in motion, the more viscous it is: thus treacle is very viscous indeed; glycerine is also very viscous; water has a much smaller viscosity, and ether, the anæsthetic, a lower viscosity still. Gases are also viscous, though, of course, very much less so than liquids: for instance, it requires a pressure to make a gas go through a small pipe, a pendulum swinging in air without any machinery to keep it going comes to rest sooner than it would do in a very high vacuum, and if air in a closed room be set in motion by a fan it soon settles down. It can be shown mathematically that this viscosity of a gas depends upon the average distance which a gas molecule goes without making a collision, and this will clearly depend upon the number and the cross-section of the molecules—that is, upon the target which they offer to the other moving molecules. Thus, if there were a hundred large balloons drifting about in a certain space, a given balloon would go a less distance without a collision than a toy balloon would do among ninety-nine other toy balloons in the same space. From viscosity measurements it can be shown that the total cross-section of all the molecules (that is, the cross-section of one molecule multiplied by the number of molecules) in a cubic inch of ice-cold air at ordinary pressure is about thirty square yards, or they would serve to make a mosaic flooring one molecule thick for an ordinary living-room. But this does not tell us how big the molecules are, because we do not know how many they are: there might be a million, each thirty millionths of a square yard across, or ten million each three millionths of a square yard across, and so on. But now suppose we squeeze the gas as much as possible, cooling it if necessary, until we liquefy it. We then believe that the molecules are nearly touching. If we measure the space into which we have squeezed the original cubic inch of gas, we then know how much space the original number of molecules takes up, and this gives us another bit of information about the number and the

size. From this and the total cross-section of all the molecules, it is easy to calculate both the number of molecules and their size.* Or instead of actually liquefying the gas, we may merely observe how it behaves when it is so compressed that the molecules come very close together: from the anomalous effects which appear, the mathematician can find out what is about the total volume of the molecules.

This method of considering the properties of gases is only one way of finding the size of molecules. Why we feel so certain that we are approximately right is that there are several other ways of finding the same thing, and they all give about the same result. When the detective finds that the footprints point to one man, he may be fairly confident, but if he finds the finger-prints, and the weapon, and the motor-car, and the button, and the other stock clues all pointing to the same man, he may well feel absolutely certain. Now a very different way of estimating molecular size is to use X-rays to investigate the structure of crystals, in which the molecules are arranged side by side, and very nearly touching. The X-rays are reflected at certain angles for crystals, and a close chain of reasoning, which we need not follow here, enables us to deduce the spacing of the molecules from the angle at which reflection takes place. The optical properties of gases can also be made to tell us something about the size of the molecules. All these methods of approach, and still others, give the same sort of size.

It can be shown, from considerations of the densities

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* To make the nature of the problem clear, we may throw it into the following very simple form: We know that a number of cubical wooden blocks, when laid out one block thick, just cover a floor of seventy-two square yards, while when built up together they will just make a large block one yard cube: how many blocks are there, and how big is a single block? The answer will be found to be 373,248 blocks, each one half-inch cube.

of gases and certain chemical facts, that there are the same number of molecules in a fixed volume (say, one cubic inch) of a gas at standard pressure, no matter what the nature of the gas may be. The different densities of different gases is a consequence of difference of weight of molecules, not of difference in number. If we know this number of molecules in a given volume of gas, and also the weight of the gas, which can be found by the use of the balance, then we should be able to find straight off the weight of the single molecule of each kind of gas. We have already spoken of one way in which this number can be found. Of recent years, however, some very striking experiments have been made, which not only give us another way of finding this number, but also prove the existence of the motion of the molecules which we have assumed to be the essence of heat. We will close this chapter by discussing these experiments, for carrying out which Professor Perrin received the Nobel Prize for 1925.

The observation from which the experiments really originate was made just a hundred years ago by the English botanist Brown. He observed that minute solid particles, which happened to be present in a plant liquid which he was examining with the microscope, were in ceaseless motion, quivering hither and thither in irregular zigzag courses. The smaller the particles, the more lively was the motion. This discovery attracted little attention, and for many years was regarded as a trivial phenomenon. Towards the end of last century, however, the true nature of the motion, which is called the Brownian movement, began to be realised. It was clearly shown that the motion of each little particle was independent of that of its neighbours, unlike the motion of the motes in a sunbeam, which move together in flocks with the currents of air. It was further established that it had nothing to do with the light falling on the liquid. We are, in fact, looking at very small, but microscopically visible, particles being jostled by the very much smaller, microscopically invisible, molecules.

Imagine a man in an aeroplane looking down on to the sea, from such a height that he cannot see the waves, and so does not know if the surface is quite calm and still, or rough and agitated. Now suppose his eye falls on a large ship, which he can plainly see, riding with engines stopped. If it is quite calm, the ship will be at rest: if, however, it is rough, the ship will be rolling and pitching, and this motion he will be able to see. It will tell him of the existence of the waves, although they are very small compared to the ship, and he cannot see them directly. In the same way the tossing of the suspended particles tells us of the motion of the molecules, although we can never hope to see them.

In science, however, before we can be sure of anything, we have not only to get a general explanation, but to make measurements and see if the size of the effects which we are explaining comes out right, so as to agree with the calculations based on the theory. Now it can be shown mathematically that if we have a lot of very small particles in a liquid, which are kept in motion by large numbers of molecules banging against them, the particles will not all sink to the bottom, as heavier particles do, but will remain suspended. There will, however, be more near the bottom than there are higher up, just as the atmosphere is denser near the ground than higher up. By measuring with the help of a microscope the number of particles at different heights, the number of molecules in a given volume of gas can be deduced. This sounds improbable, but it is so: the connecting link between the two facts is the consideration of the molecular bombardment of the particles in the one case, of molecular bombardment of other molecules in the other case.

If a little paint-water be made up with the watercolour paint gamboge, and a drop of this water be diluted until it is just feebly coloured, and then looked at under the microscope, it will be seen to be full of little spherical particles of the resinous gamboge. It was with a drop of such water that Perrin did his famous ex-

periments, or rather with a layer or film of such water, less than a hundredth of an inch thick. With a powerful microscope he counted the number of little spheres at different heights, and by various methods he found the size and weight of the little spheres. Calculating from his results, he came to the conclusion that in 1 cubic centimetre (a little less than one-sixteenth of a cubic inch) of any gas at atmospheric pressure, there are about twenty-seven million million million molecules. It follows, for example, that the weight of a molecule of oxygen, consisting of two atoms of oxygen stuck together, is about two billion-billionths of an ounce. Even if a molecule were a million million times as heavy as it is, we could not weigh it by our most refined balances. It is astonishing to think, however, that the molecule was virtually weighed by looking through a microscope at a very small drop of slightly dirty water.

The Brownian movement of the particles is a true case of perpetual motion. When we come down to so small a scale as this, all our ordinary laws have to be revised. In ordinary life we do not see a brick suddenly move upwards by itself, but a minute particle in a liquid all at one temperature, without currents in it, may, if struck by chance by rather more molecules from underneath than from above, suddenly move upwards. So, as a matter of fact, may a brick, but if we calculate the chances that enough extra molecules may hit the brick from underneath to raise it, we find that we should have to wait several million million years for it to give a good jump. Even the laziest workman might hesitate to sit on a scaffold on the off-chance that the brick might jump up to him. A microbe workman in a liquid might, however, reasonably sit on his scaffold, and wait for the Brownian movement to throw up his microscopic bricks, supposing he could build a house. The energy, of course, comes from the energy of motion of the liquid. But when we work on a large scale, there is no possibility of using the energy of a liquid in this way, unless it is hotter than its surroundings, as it is in the boiler of

a steam-engine. If the possibility existed, we might use up some of the energy of motion of the molecules in any pond, leaving the pond a little colder than when we found it. The denial that we can convert the heat of a body into work by cooling it below the temperature of its surroundings constitutes what is called the second law of thermodynamics, but this law applies to matter in bulk, and not to single molecules.

It is impossible in the restricted space of this little book to make clear the exact reasoning by which the existence, size, mass, and number of the molecules have been demonstrated. It may, nevertheless, be hoped that enough has been said in this chapter to indicate to the reader that simple experiments may be made to yield remarkable results in the hands of imaginative and experienced workers. The whole of our theories of the atom rest upon the foundation of careful measurements of observed phenomena. The methods which have been mentioned are only a few selected for their simplicity from a large number which have been devised. The strength of the present position of the atomic theory is that markedly different methods all confirm the results which have been quoted.

CHAPTER III

THE ATOM OF ELECTRICITY

A FORM of energy with which we are very familiar is that which we know as electricity. Nature occasionally gives us a striking display of electrical forces at work in the thunderstorm, occasionally, that is, at a given spot, for there is always an electrical disturbance going on in the atmosphere somewhere. It is, in fact, estimated that, when the whole earth is taken into account, there are

about a hundred lightning flashes per second taking place all the time. These phenomena are caused by the movement of large charges of electricity from one place to another, under the influence of very high voltages. If we turn from these irregular and uncontrolled displays to the well-governed behaviour of electricity in the service of man, we find that, in general, we can again reduce everything to the movement of charges of electricity. In the case of our electric lamp, or our electric motor, we have an electric current passing through a wire, and an electric current is simply a charge of electricity moving under a difference of electrical potential, just as the current of water in a river is a mass of water moving under the influence of a difference of level. In the case of our wireless waves, the disturbances which travel through space are started by large charges of electricity which are made to rush up and down the wires of the sending aerial. A charge of static electricity is generated when we rub a stick of sealing-wax on our sleeve, and attract scraps of paper, and all the common effects of electricity with which we are familiar are due to nothing but such charges in motion. It is clearly, then, a matter of fundamental importance to know the nature of this electrical charge, and, in particular, whether it can be indefinitely divided and divided into charges as small as we please, or whether there is an atom of electricity just as there is an atom of matter.

The first suspicion that there might be an atom of electricity arose from the consideration of the passage of electricity through chemical solutions of a certain nature, such as those which are used for electroplating. When the current is passed through such a liquid by means of two plates, called electrodes, immersed in it, it conveys a certain amount of the metal out of the solution on to one plate. It is found that if the same current be passed through solutions of chemical compounds of certain different metals for a fixed time, then the amount of metal deposited is proportional to the atomic weight—*i.e.*, to the weight of the atom—of that metal. This

could be explained if each metal atom, no matter what its nature, carried an atom of electric charge, as a horse carries a jockey. Certain other metals were deposited in lesser quantities than was to be expected on this theory, but then it was found that the amount moved could be accounted for on the assumption that every atom carried exactly two atoms of electric charge, or exactly three atoms of electric charge, but not a fraction of an atom of charge. This was a general argument for the atomic nature of electricity, but proof was to come from another direction.

We know that certain solids—namely, metals—will allow an electric current to pass through them, and we have just been talking of certain liquids—namely, solutions of metallic salts—which will allow a current to pass through them. Will a gas allow a current to pass? As a result of the investigation of the passage of electricity through gases towards the end of the last century, the whole trend of physical science took a new turn.

At ordinary pressure, it requires enormous voltages to force a current through an air gap of any length, and when the current at length passes it does so as a rending spark. But suppose we take a glass tube, inside which are two metal plates, joined to rods which pass out through the glass, so that we can connect them to a source of high potential, or tension, as it is often called. The plate connected to the negative pole of our high tension battery or induction coil we will call the cathode plate, or simply cathode: the plate connected to the positive pole is called the anode. Now, if we pump out the air from the tube, at a certain stage a luminous discharge passes from one electrode to the other, the colour of which depends upon the gas present. As the pressure is made lower and lower, the appearance of the discharge goes through a variety of beautiful changes until when the pressure in the tube is reduced to only a few hundred thousandths of ordinary atmospheric pressure, something new happens. The walls of the tubes opposite the cathode begin to glow with a greenish light, and, by

having in the tube some body which casts a shadow, it is easy to show that the glow is due to something shot off by the cathode, which affects the glass where it strikes it. It is easy to limit the rays so that they form a narrow beam. The investigation of these streams from the cathode, the so-called cathode rays, led to the discovery of the electron, or atom of electricity.

When a magnet is brought near, the beam of cathode rays is bent aside, as can be seen by the movement of the bright spot formed where it strikes the glass of the tube, or a phosphorescent screen put inside the tube. The beam behaves just like a current of electricity, on which, as is well known, a magnet exerts a force, the direction of its movement being the same as if a negative charge of electricity were moving away from the cathode along the rays. It was soon proved in another way that the rays did carry a negative charge—namely, by catching them in a metal vessel and measuring the charges acquired by the vessel. The cathode rays can therefore be explained as a stream of electrified particles, and it might at first be supposed that they were atoms, each carrying a negative charge. When the man of science has to decide on such points, however, he always tries to measure the size of the effects in question, so that the problem arose of measuring the charge and the mass of the flying particles, and incidentally of proving that the rays did consist of flying particles.

The amount of the bending of the narrow beam of cathode rays produced by a magnet of known strength will give us some information on this point. In order to understand how this is, let us consider a simple illustration. Suppose that we wanted to know whether a ball were heavy or light, without being able to weigh it directly. If it were dropped, and a wind of known strength were blowing across, we could find out something about its weight from the amount by which it was blown out of the straight line. We could, however, definitely calculate its weight only if we knew the force which the wind exerted on it, and the height from which

it was dropped, that is, the speed of the ball. In the same way, in the electrical case, the deflection by a *magnetic* field only gives us the mass of the flying particle if we know its speed and the force which the magnet exerts on it, and we do not know this force unless we can find out the charge on the particle. The amount which an *electric* force, such as that produced between two condenser plates charged to different potentials, sweeps the particle aside can also be measured, and tells us something: in fact, the electric and the magnetic deflections together enable us to calculate both the velocity of the particle and the ratio of the charge to the mass of the particle, although not both the charge and the mass separately. To use our illustration, we blow the cathode stream aside by two different kinds of wind, obeying different laws. This was one way in which Sir J. J. Thomson, the famous head of the Cavendish Laboratory in Cambridge from 1884 to 1919, and Nobel prizeman in 1906, who celebrated his seventieth birthday in 1926,* determined that the speed and the proportion of charge to mass, of the flying particles made it most unlikely that they were charged atoms of matter: they must be something lighter.

If we could find the charge on one particle we should know its mass as well, since we have seen how to measure the proportion of the charge to the mass. This was done in Cambridge many years ago by a very ingenious

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* On the occasion of a visit to America, Sir J. J. Thomson, who was at the University of Princeton, found that it was impossible for him to get to New York by any ordinary means in time to catch his boat home. An offer was made to him by the competent authorities to stop the transcontinental express from the West Coast to New York. They explained that the express had never been stopped for anybody, not even the President of the United States, "but," they said, "we will stop it for J. J. Thomson." The express was duly stopped, and the Cavendish professor caught his boat.

method. However, the most accurate measurements of the charge have been made more recently in America by Professor Millikan, who in 1923 obtained the Nobel Prize for this work. His method will be described at the end of this chapter. We now turn to the further consideration of the nature of the particles which constitute the cathode rays.

The charge on one of these particles is the same as the charge which we find on atoms by the experiments on passing electricity through solutions of metallic salts, but the mass of the particle is much less than (little more than one two-thousandth of) that of the lightest atom known, the hydrogen atom. The particles are, in fact, little atoms of negative electricity all by themselves, not sitting on atoms as they are in liquids, but absolutely free. It may be asked why, in that case, they have any mass at all. The answer is that it can be shown that to move a charge of electricity, if it be concentrated into a very small space requires a force—that is, the charge tends to resist being made to go faster, or possesses inertia, as we say. In this way it behaves just like an ordinary mass. In fact, if the measured charge be crowded into a minute sphere a little greater than one ten-million-millionth of an inch across, it can be shown that it will have just the mass measured experimentally.

These atoms of pure negative electricity are called electrons. The cathode rays, of which we have spoken, are streams of electrons shot off by repulsion from the cathode along the exhausted tube. But these exhausted tubes are not mere playthings of the man of science, good only to advance abstract knowledge. If we put inside such a tube a heavy piece of metal opposite the cathode —the so-called anti-cathode—something very remarkable takes place when the discharge is passed, so that the stream of electrons strike the anti-cathode. The anti-cathode gives out X-rays. Every X-ray tube, used in hospitals, of whatever pattern, consists of a lump of metal in a highly evacuated tube, bombarded by very swift electrons. Even if there be no lump of metal we

get X-rays, although not very penetrating ones, generated where the cathode stream hits the glass: they are produced whenever very swift electrons encounter matter of any kind. The rays were, in fact, discovered in 1895 by Röntgen, proceeding from the walls of an evacuated glass tube.

Now electrons can be obtained from a variety of sources in a variety of ways. If any metal be raised to red heat, it gives off electrons. A very familiar instance of this is the so-called valve used in wireless sets. Such a valve contains a wire which is heated by the passage of an electric current, and this wire gives off a stream of electrons, which is utilised to magnify the electrical effects which it is desired to observe—namely, the changes in the electric force produced by the broadcasting waves. Electrons are also set free from metals when violet or ultra-violet light, or X-rays, fall upon them, a fact which has been utilised for measuring the strength of weak lights, for the stronger the light, the more electrons are given off. In whatever way, or from whatever substance, the electrons are produced, they are always the same atoms of electricity—that is, they have the same charge and the same mass. The electrons produced in a tube containing a trace of hydrogen gas are the same as those in a tube containing a trace of air, and are the same as those produced from a hot wire, whether it be of platinum or of tungsten, and the same as those produced from a plate of metal, whether it be zinc or iron, on which ultra-violet light is falling. The atom of negative electricity is unique and indivisible.

We have spoken of the atom of negative electricity: can we get an atom of pure positive electricity? The answer is: No. In an exhausted tube flying positive charges can be produced and detected by certain means, but they are always thousands of times heavier than the electron, and prove to be not isolated positive electricity, but atoms of matter with a positive charge. We can, for instance, have positive rays consisting of charged hydrogen atoms, or positive rays consisting of charged

nitrogen atoms. What actually happens is that we can knock or shake one or more electrons, particles of pure negative electricity, out of an atom, and when we do this we leave behind a positively charged atom. We cannot shake a particle of positive electricity out of an atom, and leave behind a negatively charged atom: we can have negatively charged atoms, but they are simply ordinary neutral atoms with one or more extra electrons sticking to each. Perhaps a fanciful illustration may be allowed. Let us suppose that a man contains two principles, good and evil, and for convenience let us compare the good to positive electricity, the evil to negative electricity. Let us further suppose, without any theological implications, that a normal man contains both principles in equal quantities, so that on the whole he is neither good nor bad. To illustrate the electrical case, we must suppose that we could remove some of the evil from a man as an unattached essence, leaving behind a rather good (positively charged) man, and obtaining the evil principle without a human home. Let us say that we have cast out the devil from the man. We cannot, however, if our illustration is to hold, remove some of the good as a pure essence, leaving a rather bad man: we never hear of casting out angels from a man. Virtue, or positive electricity, must have some material seat. I do not wish to suggest that this analogy has any moral meaning: it is given merely to try to make clear the essential difference between positive and negative electricity.

The lightest atom is the atom of hydrogen, and the lightest positive charge which we can get is therefore the positively charged atom of hydrogen. It is an atom of hydrogen which has lost an electron—in fact, its one and only electron, for a neutral hydrogen atom only has one. This positively charged atom of hydrogen plays a very important part in modern physics: it is a unit of positive electrification, and is often called a proton. We shall have to refer to it when we discuss the structure of the atom.

Electricity is, then, atomic in nature. The atom of electricity cannot be split up, or broken, and all electricity must be supplied in these little units. The atom of electric charge—that is, the charge on the electron—is exceedingly minute. In an ordinary electric lamp some million million million electrons per second pass a given point in the wire. If, instead of having an electric meter, we had to count the individual electrons passing through our lamp filament, it would take all the inhabitants of the earth, counting night and day as fast as they could go, two years to number the electrons which had passed through the lamp in one second. Yet, notwithstanding its smallness, the charge on the electron has been measured with an accuracy of one part in a thousand. The principle of the most accurate method used by Millikan is quite simple, and we may fittingly close this chapter by describing it briefly.

By means of a spray, a very few minute drops of oil, or some other liquid, are produced in the space between two horizontal metal plates, which can be electrically charged. In the ordinary way the droplets settle down very slowly through the air, at a rate which can be accurately measured. The rate depends upon the size—the smaller the droplet, the slower it falls (except in a high vacuum, where all bodies fall at the same speed). By means of X-rays or some other agent, a number of electrons and electrically charged atoms or molecules are produced in the air surrounding the droplets, and a droplet will occasionally pick up a positive or negative charge—that is, an electron, or an atom with an extra electron or an atom short of an electron. When it does so, it is attracted by one of the charged plates, and, if the electric field be suitably adjusted, the fall of the droplet, whose motion is studied through a microscope, can be checked. It remains suspended, gravity pulling it down, and the electric force pulling it up. Sooner or later, after the droplet has been stationary for some time, it will suddenly begin to move up or down. This means that it has picked up another charge, either positive or negative.

The electric force between the plates can then be readjusted, and the droplet kept steady again.

Now if the weight of the droplet be known (and it can be accurately found by special methods) we know the force with which gravity is pulling it down, and if we measure the strength of the electric field, we can calculate what the charge on the droplet must be for it to experience the upward pull which just counterbalances the downward pull of gravity. The experiment is thus very simple in its essence, and merely consists in measuring the electrical pull, exerted by an electric field of measured strength, on a tiny charged drop of oil weighing about a million million to the ounce. In this way Millikan found that the charge which a droplet can pick up is always one or two or three, or some other very small number of times a unit charge, and never anything in between. The unit charge can be calculated, and is found to be just about the magnitude which had already been found by other ways for the charge on the electron. The droplet is so small that it collects only one electron, usually sticking to an atom, at a time. No matter how the electrons and charged atoms be produced, no matter what the nature of the droplet, whether oil or quicksilver, the same result is obtained. We are confident that the unbreakable atom of electricity does exist, and we know the magnitude of its charge with a greater accuracy than most of us know our own weight.

CHAPTER IV

THE NATURE OF LIGHT

We shall see when we come to consider the way in which atoms are made that it is necessary to know something about the nature of light. Every kind of light originates

in some material source—a glowing solid, an incandescent liquid, such as molten iron, or a gas through which an electric discharge is passing. In other words, every light has its beginning in atoms, and it is not surprising that we can learn something about atoms by studying light.

A very slight study of the great source of light which nourishes us, the sun, will suffice to tell us some of the most important properties of light. The atmosphere which surrounds our earth is only a comparatively thin layer, for at a height of ten miles the air is only one-tenth as dense, and at a height of a hundred miles is already only one ten-thousand-millionth as dense, as it is at the surface of the earth. The sun, however, is about ninety-three million miles distant. This shows us that light must be able to pass freely through absolutely empty space where no atoms are, in contradistinction to sound, which requires an atmosphere of some kind, or a solid, or a liquid, to convey it. Further, we know that the sun's rays heat bodies on which they fall; in fact in Egypt there are engines which are worked by using concave mirrors to concentrate the radiation on metal boilers, in which steam is generated. This shows us that the rays which traverse empty space are a form of energy, since we know that heat is a form of energy, and anything which can be turned into heat must itself be a form of energy.

The speed with which light travels can be measured either from certain astronomical observations, or by very accurate experimental methods which have been worked out. It is very great, about 186,000 miles a second, which means that the light from the moon takes about one and a fifth seconds, while that from the sun takes some five hundred seconds to reach us. It may be remembered in passing that stars are so far distant from us that the time taken by light to reach us from even the nearest stars is measured in years.

Light, then, is a form of energy which traverses space where no matter is, with a very high speed. Now Sir

Isaac Newton first showed how sunlight can be spread into a coloured band, or spectrum, by means of a prism, and proved that all the colours of the spectrum must be contained in the sunlight, and merely separated out by the prism. The colours of the spectrum form a continuous range, in which the following can be seen as distinct by a man with good colour vision: red, orange, yellow, green, blue, indigo, violet, in that order. It is found, however, that there are rays beyond the red, which are invisible to the eye, but can be detected by their heating effects, which are comparatively large: these are the so-called infra-red rays. Similarly, there are invisible rays beyond the violet: these have a comparatively small heating effect, but have certain other actions on matter, of which the most notable is that they affect a photographic plate just as visible violet light does. They are called the ultra-violet rays, and it is characteristic of the vigorous action, of a chemical nature, which they can produce, that the sunburnt colour of people exposed to the summer sun is due to a narrow region of ultra-violet rays, and not to the heat or the visible light.

Now it is known that light has the properties of a vibration, or wave motion. By certain delicate optical adjustments it can be proved that two different beams of light can, if the right conditions be present, be made to support one another at certain places, and cancel one another at others, or "interfere," as it is called. This can only be explained by supposing that the light behaves like waves, and that, when the right disposition of apparatus is made, the waves in the two different beams are in step at some places, and out of step in others, so that at some places the crests fall together, and reinforce one another, while at others the crest of one train of waves falls in the trough of another, and the waves cancel one another, producing the interference pattern. Means are known of measuring accurately the wavelength of the light, and it is found that, in the spectrum, a difference of colour corresponds to a difference of wave-

length. The wave-length of visible light is extremely minute. For deep red light, which has the longest waves of the visible spectrum, the wave-length is about thirty millionths of an inch, of green light about twenty millionths of an inch, and of violet light about sixteen millionths of an inch. The ultra-violet comprises still shorter wave-lengths, while the wave-lengths of the infra-red are longer than any so far cited. That we see only a certain restricted range of wave-lengths is due to the constitution of our eye, and not to any inherent property of these particular waves.

Light, then, has the properties of a wave-motion, which traverses space in which there is no material substance whatever, not even the most rarefied gas. In order to obtain some sort of an explanation of this vibration passing through emptiness, the idea of an ether of space was evolved, the said ether being supposed to be some non-material substance which filled all space, whether the space was empty, or occupied by matter. If the space was occupied by a substance, the ether was supposed to pass freely between the atoms of the substance, as the air passes freely between the trees in a forest. The ether then vibrates, just as a jelly filling all space might vibrate if given a shock at any point, which would become the centre of waves spreading out in all directions. The ripples which spread out over the surface of a pond when a stone is dropped in give an even simpler representation of the light-waves spreading out from a source of light. However, it is difficult nowadays to maintain the existence of an ether of space with the properties of an ordinary elastic solid, for if such an ether really existed, we should be able to measure our passage through it, and find out if we were moving, not with reference to other material bodies, but with reference to the universal ether. Experience and the theory of relativity tell us that we cannot do this, so that to-day it is usual to say that light-waves travel through empty space, but that we don't know how they do it, although we know the speed with which they

travel. They leave the light source, and after an interval of time they appear at the eye or the observing instrument.

Now visible light, with its close companions, the ultra-violet and the infra-red, is not the only kind of radiation that travels through empty space. The waves of wireless telegraphy and broadcasting do the same, and actually travel at the same speed as light. Their wave-lengths are, however, enormously greater than those of light, being measured in yards and hundreds of yards rather than in hundred-thousandths of an inch. X-rays also travel through empty space, and have been proved to be waves, but of wave-length much shorter than even the ultra-violet. Classes of X-rays of different penetrating powers are known, and the shorter the wave-length of the X-rays the greater their power of penetrating. Those used in hospitals in the ordinary way have a wave-length of a few hundred-millionths of an inch. Radium gives out a class of rays called gamma-rays, which are just like X-rays, but still more penetrating, with wave-lengths as short as twenty-two million-millionths of an inch.

We have, then, various classes of waves which pass through empty space, whose properties depend upon the wave-length. The ultimate nature of all these waves is the same: they all originate in some kind of electrical disturbance, even the light waves, as we shall see later, and their passage consists of a rapid oscillation of electric and magnetic forces. As a water wave passes us, the height of the water at a given place increases and decreases, and goes on doing so as long as the train of water waves is kept up. The water does not travel on with the waves: if a stone is dropped into a pool, the water that was at the place where the stone fell does not move out with the ripples, but stays where it was, bobbing up and down, and in the same way the water at other places bobs up and down. In an electro-magnetic wave, the electric force at any point bobs up and down, diminishing from being large in one direction to being

nothing, and then reversing until it becomes large in the opposite direction, when it again diminishes, and so on. Changes of electric force are always, by their very nature, accompanied by changes of magnetic force which take place at the same rate, which is why the waves are called electro-magnetic. All electro-magnetic waves travel in empty space with the same velocity, that of light. Wireless waves and X-rays both originate in an artificial electric disturbance produced by our control of electrical apparatus, and both are electro-magnetic waves, just as Atlantic rollers and the pond ripples on a calm day are both water waves. The wave-length of the wireless wave is about a million million times that of the X-ray, and this difference of wave-length is what gives the difference of properties. The following table indicates the wave-lengths of the different classes of waves, but, of course, there is no hard and fast limit to be set for any particular kind of waves.

ELECTRO-MAGNETIC WAVES

Kind of Wave.	*Wave-length.*
"Wireless" waves	20 miles to 3 yards, say 1,300,000 inches to 100 inches.
Waves produced by other electrical oscillators	100 inches to $\frac{1}{80}$ inch.
Infra-red	$\frac{1}{80}$ inch to $\frac{3}{100000}$ inch.
Visible light	30 to 15 millionths of an inch.
Ultra-violet	15 to $\frac{1}{2}$ millionths of an inch.
X-rays	50 to 1 thousand-millionths of an inch.
Most penetrating gamma-rays	22 million-millionths of an inch.*

* The longer gamma-rays coincide with certain short X-rays.

We have discussed the atom of matter and the atom of electricity. Is there such a thing as the atom of radiant energy? Various lines of investigation have culminated in the so-called quantum theory, which answers this question in the affirmative. It appears that we cannot have radiant energy given out in small quantities of any size whatsoever, but that there are small units of radiation, and that whenever we have an emission of light, it consists of one or a number of these units. Just as if we buy tobacco in the form of cigarettes we cannot purchase less than a certain weight of tobacco, but must always have at least one cigarette-full, and in any case a whole number of times a cigarette-full, so when we receive radiant energy in the form of radiation we cannot have less than a unit, or quantum, as it is called, of energy.

However, the unit of radiant energy has the peculiar feature that it is not of a fixed and determined size for all kinds of radiations, but depends upon the wave-length of the radiation. It is easier to describe the way in which it depends if we speak of the frequency of the radiation, which is the number of vibrations a second, or the number of complete waves which leave the source in a second. As the velocity of all kinds of electromagnetic radiation is the same in free space, it can easily be seen that the longer the wave-length the smaller the frequency. Thus, the frequency of a wireless wave whose wave-length is 100 yards is $186{,}000 \times 17 \cdot 6 = 3{,}273{,}600$ vibrations a second, since the velocity is 186,000 miles per second, while the frequency of a kind of violet light, whose wave-length is sixteen millionths of an inch, is $186{,}000 \times \frac{1{,}760 \times 36}{16} \times 1{,}000{,}000 = 186{,}000 \times 110 \times 36{,}000{,}000 = 746{,}560{,}000{,}000{,}000$ vibrations a second! The frequency of X-rays may be many thousands of times as great.

Now the unit, or quantum, of radiant energy is obtained by multiplying the frequency by a certain fixed number (called Planck's constant, after the German physicist who

originated the quantum theory, and was awarded a Nobel prize in 1918), which is very, very minute, so that even when huge numbers like that just cited are multiplied by it the result is still very small. This means that the quantum, or unit quantity, of X-ray energy is many thousands of times as great as that of visible light, which again is many millions of times as great as that of wireless-wave energy. To continue our cigarette analogy, it is as if cigarettes of the most diverse sizes existed, some as big as a steamship funnel and others the smallest size made for ladies, so that when we bought one kind, the large kind, our unit weight of tobacco was tons, while when we bought the other, it was in a small fraction of an ounce. For a given size of cigarette (corresponding to a fixed frequency, or wave-length) we should, however, only be able to buy tobacco in steps of weight—half a cigarette is not sold. Half a quantum of radiant energy cannot be emitted.

What has just been stated about the quantum of radiant energy is the result of a prolonged consideration of certain experimental results, and not of argument as to what ought to be true. We cannot see any particular reason why energy should thus be radiated in bundles, as it were, and not in any amounts whatsoever. Everything, however, points to such a granular emission rather than a continuous emission, just as matter has a granular structure and not a continuous structure. Since all matter consists ultimately of atoms, all radiation of energy by matter must ultimately be a radiation from atoms, but we must imagine radiant energy being thrown out from an atom in pailfuls, as it were, rather than from a hose pipe. A pailful is called a quantum of radiant energy, and the size of the pail depends upon the wave-length of the radiation.

The conclusions of modern science, then, are as follows:

1. All matter consists ultimately of atoms, and there are about ninety different kinds of atoms, corresponding

to the different chemical elements. All known substances which are not chemical elements are formed ultimately by the combination of chemical elements—that is, by the combination of atoms.

2. Negative electricity is made up of atoms of pure negative electricity, called electrons, which can have an existence independent of matter. There is only one kind of electron. Positive electricity can only exist in combination with matter, and all positively charged atoms of matter are merely atoms which have lost one or more electrons.

3. All radiant energy is of an electro-magnetic character, and can be emitted by atoms only in separate packets of energy, called quanta. The amount of energy in a packet depends upon the frequency of the radiation, being, in fact, proportional to this frequency.

We have the three totally different kinds of atoms: the atom of matter, the atom of electricity, and the atom of radiation. We can now proceed to inquire how these three are combined in the modern theory of the structure of the atom.

CHAPTER V

THE STRUCTURE OF THE ATOM

UNTIL the past century was nearing its close, it was generally believed that every atom was a complete unbreakable particle, a "manufactured article," as Clark Maxwell called it, which was exactly like every other atom of the same element. It was also believed that the eighty odd different kinds of atoms were eighty different patterns, or models, as it were, which had nothing in common with one another, so that, to use an engineering simile, they resembled eighty different kinds of castings

made from eighty different kinds of moulds, rather than eighty different structures, all built up from the same kinds of bars and rivets, arranged in different ways. If we believe to-day that the latter analogy represents the true state of affairs, it is because the advance of knowledge has revealed to us the existence of minute entities which can play the part of the bars and rivets, while thirty years or so ago there seemed to be no materials for atom building.

It is true that about a hundred years ago an English chemist, Prout, suggested that all atoms were assemblies of the lightest atoms—namely, hydrogen atoms, arranged in different ways. If this were true, however, we should expect all the heavier atoms to weigh some exact number of times a hydrogen atom, just as if a structure were built up of a number of similar bars (the weight of the rivets being negligible) it would weigh an exact number of times the weight of one bar. It is found, however, that the atomic weights are not in general exact multiples of the atomic weight of hydrogen, nor of any weight of that kind, but have often fractional parts. As we do not admit that a hydrogen atom can be broken into smaller atoms, this question of fractional parts in the atomic weight would appear at first sight to put out of court the suggestion that the hydrogen atom is a bar, or brick, from numbers of which heavier atoms can be built. We shall see, however, that the researches of recent years have provided a solution of the riddle.

We have seen that electrons can be obtained from any kind of matter, solid, liquid, or gas—that is, from any kind of atom—and that they are very much lighter than any kind of atom, a single electron having a mass little more than one two-thousandth of the mass of the hydrogen atom. It is therefore clear that the electron must be a constituent part of the structure of all atoms. But electrons have a negative charge, so that, since atoms as a whole have no charge in the ordinary way, each atom must contain a positive charge to neutralise or annul the negative charge of the electrons. The whole modern

theory of the structure of the atom deals with the arrangement of the positive and negative electrical charges in the atom. We will first of all describe briefly how the atom is built, and then refer to one or two of the experimental investigations which have given us this knowledge.

Even the heaviest atom contains only two hundred or so electrons, while the lightest atom, hydrogen, contains only one. We have already mentioned that the mass of the hydrogen atom is nearly two thousand times that of the electron, while the mass of the heaviest atom, uranium, is just over 238 times that of the hydrogen atom. Hence it is clear that the atom cannot owe its mass to the electrons in it, but must have another constituent part, much more massive than the electron. All the evidence goes to show that this heavy part is associated with the positive charge, and that an atom is a structure of the following kind:

At the centre is a positively charged particle, called the nucleus, which is very much smaller than the atom itself; in fact, only about a ten-thousandth as big across. This nucleus is the heavy part of the atom, or in it is concentrated practically all the mass of the atom. Round it electrons, whose mass is minute compared to that of the nucleus, circulate in orbits, as planets circulate round the sun. The number of electrons is such that, when the atom is in its normal state, they just annul the positive charge on the nucleus. In a moderately heavy atom there are orbits of various sizes, each traced out by an electron. The size of the outside orbits is what we call the size of the atom, since when two atoms are brought together, the outside electrons repel one another,* and unless the atoms hit one another with great velocity, these outside electrons guard the space they patrol from

* Electric charges of the same kind, positive and positive, or negative and negative, tend to move apart, while charges of different kinds, one positive and one negative, are attracted to one another.

the outside electrons of other atoms. Instead, therefore, of thinking of an atom as a solid sphere, we must think of it rather as a plum, round which a swarm of gnats fly in fixed curves, gnats of bellicose disposition who prevent gnats belonging to other plums from coming within the sphere which they guard. Supposing the size of a plum to represent the size of the nucleus, the space occupied by the gnat swarm will be about two thousand feet across. The atom is mostly empty space, and what little there is, is electricity.

The hydrogen atom is the lightest and simplest of all atoms. It consists of a nucleus whose mass is practically that of the whole hydrogen atom, with a unit charge, by which we mean a positive charge whose amount is the same as the amount of negative charge on a single electron; round this a single electron moves in an orbit. The hydrogen nucleus is so important for the question of atomic structure that a special name has been given to it. It is called a proton.

Since practically the whole mass of the atom is concentrated in the nucleus, in heavier atoms the nucleus is heavier: it has also a higher positive charge. We naturally want to know if these heavier nuclei are each an entirely fresh entity, with no connection with any other nucleus, or if they are built up of simpler units. Since our unit of positive charge is the proton, it naturally occurs to us to inquire if nuclei heavier than that of the hydrogen atom are made up of protons held together by some forces which we do not fully understand. At first sight, two objections to this theory arise, which can, however, both be overcome. To begin with, if heavy nuclei were simply made up of protons, each with the mass of the hydrogen atom (which we may call unit mass) and each with unit positive charge, the number of units of mass in a nucleus would always be equal to the number of units of positive charge. An atom twenty-three times as heavy as a hydrogen atom would have a nucleus with twenty-three times the positive charge on the hydrogen nucleus, and would neces-

sarily have twenty-three electrons circulating round the nucleus, if the atom was to be neutral as a whole. It is found, however, that in heavier nuclei the number of units of positive charge is always less than the number of units of mass: sometimes it is about half the latter number, but often less than that. This can, however, be simply explained, if we suppose that the nucleus itself contains electrons as well as protons, for the electrons add practically nothing to the mass, but each one annuls a unit of positive charge. A nucleus containing twenty-three protons and twelve electrons would have a mass of twenty-three units, but a net positive charge of only eleven times that of the hydrogen atom, and so would be surrounded by eleven planetary electrons, as distinct from the twelve done up in a little bundle with the nucleus. The particular numbers quoted apply to the sodium atom.

The second objection is that if all nuclei are made up of protons, the mass of all nuclei would be an exact number of times the mass of the hydrogen nucleus, and so all atoms would have atomic weights which were simple numbers without fractional parts. It has been already mentioned that fractional atomic weights are actually found; for instance, the atomic weight of chlorine is neither 35 nor 36, but 35·46. The explanation of this fact is one of the most important discoveries of modern physics, and will now be discussed.

The net positive charge on the nucleus fixes the number of electrons which circulate round the nucleus. This in its turn fixes the chemical properties of the atom—that is, the way in which it combines with other atoms. For since when atoms are chemically combined, they are held together by electric forces, the combination must be governed by the number and arrangement of the outside electrons of the atom, and this is determined by the total number of electrons present. Now if we suppose that in some way or other an electron and a proton are added to the nucleus, the mass will be increased by one unit (*i.e.*, by the mass of a proton), but the nuclear charge

will not be changed, so that we shall have a heavier atom, with the same chemical properties as a lighter atom. If two protons and two electrons be added, the mass is increased by two units, but once more the charge, and hence the chemical properties, is unchanged. This theory, then, allows us to account at once for the existence of atoms of the same chemical properties, but different masses. Before the nuclear theory of the atom was evolved, it was always supposed that atoms of the same chemical properties had the same mass.

This belief in the existence of atoms of different masses endowed with the same chemical properties is not an unsupported fancy. By experimenting with evacuated tubes, in which by suitable arrangement a stream of flying atoms with positive charges can be obtained, passing in the opposite direction to the flying electrons which constitute the cathode rays, the masses of the atoms of a gas introduced in minute quantities into the tube can be measured. This was first done by Sir J. J. Thomson. His work has been very much extended by Dr. Aston, who devised new and very accurate methods of applying electric and magnetic forces to measure the mass, for which work he was awarded a Nobel prize in 1922. He showed that in ordinary chlorine gas, for instance, there were some atoms whose mass was 37 units, but a smaller number whose mass was only 35 units, the proportion being such that the *average* mass was 35·46. All elements whose atomic weights contain fractional parts are similarly mixtures of atoms of different whole number atomic weights, all having the same chemical properties. Sometimes there are as many as seven different masses for atoms of the same chemical properties.

Atoms which have the same chemical properties, but different masses, are called *isotopes*, which means elements having the *same place* in the table which expresses chemical properties. In short, we may say that all elements with fractional atomic weights are really mixtures of isotopes. The isotopes cannot, of course, be separated by chemical means, since they all behave in

the same way towards all chemical tests. If there are several different men of the name of Smith, it is no good expecting to separate them by having a roll called. There are, however, certain non-chemical methods of separating isotopes, which make use of the difference of mass of the atoms, but they are very slow and laborious, and it is not feasible to effect a complete separation by their help.

To summarise, we may say that the atom has a very open structure, consisting of a very minute, comparatively heavy nucleus, with a net positive charge, and circulating electrons, in such number that their total negative charge equals the net positive charge on the nucleus. The nucleus itself contains both protons and electrons, the protons being responsible for practically all the mass, and for the positive charge, while the electrons annul part of the positive charge, and contribute practically nothing to the mass. The dimensions on which this system is built may be illustrated by reference to the atoms of an element about halfway on the list, as far as weight and complexity are concerned—namely, silver. There are two isotopes of silver, one with mass 107, and the other with mass 109 times that of the proton, while the number of units of net positive charge on the nucleus is 47. One isotope of silver therefore has 107 protons and 60 electrons in the nucleus, while the other isotope has 109 protons and 62 electrons in the nucleus. The nucleus is about one two-million-millionth of an inch across; the nearest planetary electrons, two of them, are at about a hundred times this distance from the nucleus. The outermost electron is tracing out a path which is, roughly speaking, about a hundred-millionth of an inch across. That is, if the nucleus be imagined to be about the size of a billiard-ball, the distance of the nearest electrons will be somewhere about the distance from the centre of the table to the walls of the billiard-room, while the distance to the outside electrons will be about half a mile. In lighter atoms, the nearest electrons are somewhat more remote from the nucleus, but there are fewer planetary

electrons: in heavier atoms the nearest electrons are nearer to the nucleus, and there are more planetary electrons. The examples quoted, however, will suffice to show how open is the structure of the atom.

An atom is empty space which has peculiar properties because of the presence of a few specks of electricity. The hardness of solids is due to the difficulty of forcing the atoms closer together, for the electrical forces of repulsion between the different atoms become very large when they are made to approach a little nearer to one another than their normal positions. These forces can, as a matter of fact, be calculated from the compressibility of crystals—that is, from the force required to squeeze the crystal in by a given small amount.

We can now say a word as to one or two types of experiment by which this scheme of atomic structure has been established. If the structure of the atom is as loose as we have said, it should be possible for particles to pass right through it, if they are only small and swift enough. Now we know that the electron is very small, even compared to the size of an atom, and by applying high voltages electrons can be made to travel very swiftly in a cathode beam. Many years ago, Professor Lenard, who was awarded a Nobel prize in 1905, observed that the cathode rays produced in an evacuated tube could be made to pass right through a thin foil of aluminium or other metal, used as a window, out into the air. He showed that the penetration obtained could only be explained if the swifter electrons could pass right through the atom, and this was the first proof of the emptiness of the atom.

There is, however, another class of very minute projectile at our disposal. The so-called radio-active substances give out of their own accord three different types of radiation, to which the names alpha, beta, and gamma rays have been given. The gamma rays we have already mentioned as a kind of very penetrating X-rays, a kind of wave analogous to light-waves, but of extremely short wave-length. The beta rays are very swift electrons,

which the nuclei of radio-active atoms shoot out spontaneously. The alpha rays are even stranger; they consist of a stream of particles which are the nuclei of helium atoms—that is, nuclei of mass four and net positive charge two, the helium atoms being the next heavier after hydrogen. (Atoms of mass two and mass three have never been detected.) These alpha particles are fired out with a speed of some ten thousand miles a second, and so, in spite of their lightness, have a comparatively large energy. It must not be thought that all radio-active substances send out all three kinds of radiation, but rather that when all the radio-active substances are considered, all these types of radiation will be found to be frequently represented. The velocity of the alpha particles is not the same for all parent substances, but it is always in the neighbourhood of the figures cited.

These alpha particles have the very important property that, when they hit certain phosphorescent substances, they cause minute splashes of light, as it were, which can be seen through the microscope as scintillations. When radium, the most famous of the radio-active substances, was first discovered, a little instrument called the spinthariscope aroused great interest. It consisted mainly of a screen prepared by covering a little plate with a phosphorescent substance, of a speck of a substance containing radium, and a lens to observe the little flashes on the screen. What was then little more than a toy has been turned by Sir Ernest Rutherford, the present head of the Cavendish Laboratory at Cambridge, who obtained a Nobel prize in 1908, into a very powerful weapon of research. For each tiny spark of light gives us the place where a single alpha particle hits the screen, just as the splash of a bullet in water would betray the arrival of the invisible bullet at the water surface. Hence we have a means of investigating what happens to alpha particles, although we cannot see them. We may speak of them as one speaks of a pushing individual, and say that they are so energetic that they make a splash.

Alpha particles pass through thin foils of metal to a

degree that shows that they can penetrate right through individual atoms, and are not just passing between them. However, our little phosphorescent screen, together with a low power microscope to look at it, can be made to tell us something more about the passage—namely, how much different particles are turned aside in passing through the foil. It is as if we were firing bullets through a mud wall, say, and detected what happens to them by having a wood screen parallel to the wall, and observing by means of the flying splinters the place where the bullets struck the screen.

When such experiments are carried out, it is found that some of the alpha particles are turned aside through very large angles by passage through the foil. Sir Ernest Rutherford showed that the number so turned aside could not be explained as a result of a lot of little deflections by different atoms, but must be due to something small, very heavy, and with a large electric charge, existing among the atoms. From these experiments he deduced the nuclear structure of the atom. In our illustration of the mud wall, if we found that a fair number of bullets were deflected through very large angles in passing through the wall, we should deduce that the mud contained stones. By calculation the number of alpha particles turned through different angles may be made to tell us how heavy and how highly charged the nucleus is, and, in fact, these experiments on the scattering of alpha rays have been, and are, our main source of knowledge about the nucleus.

By a very ingenious process, invented by Professor C. T. R. Wilson, the whole path of an alpha particle can be rendered visible, although each alpha particle is only the nucleus of a comparatively light atom. An alpha particle flying through a gas knocks the atoms about, dislodging electrons from their outer parts, which electrons may then stick to other atoms, so that we have both positively and negatively charged atoms present. Now, if the air contains more than a certain amount of moisture in the form of invisible vapour, the moisture

will condense into tiny drops if it only has something to give it a start, to form a beginning of a drop, just as a cork may form the beginning of a ball of wool. A speck of dust will serve the purpose, but so will a charged atom, or even an electron, and this fact has an important bearing upon the rainfall, which cannot be considered here. For our present purpose, what is important is that the alpha particle in its passage creates a number of charged atoms on which moisture can condense in minute drops. If the particle be traversing moist air, and the air be suddenly cooled so that the moisture wants to settle, a number of tiny drops will be formed which define the path of the particle in a visible way. The drops are so small and so close that, with suitable illumination, the path of the particle appears as a clearly defined white line. It is as if a bullet were fired through a cornfield and a flock of pigeons promptly settled on the broken ears, defining the invisible path of the bullet. The devices by which the experiment is made to work successfully are extremely ingenious: for instance, the cooling of the moist air is produced by a slight expansion of the air, and the paths are photographed by the momentary flash of a spark. Certain of these alpha rays tracks show clearly a sharp elbow in the path, which takes place when the particle happens to pass near the nucleus of an atom of the gas through which it is passing, but, owing to the smallness of the nucleus, most of the alpha particles get through without passing sufficiently close to a nucleus. From a study of the tracks, a great deal of information as to the nucleus has been obtained.

CHAPTER VI

HOW THE ATOM SENDS OUT RADIATIONS

We know that the atom, when suitably stirred up (or excited, to use the scientific term) can give out electromagnetic waves which are called infra-red, visible light, ultra-violet, or X-rays, according to their wave-length. We have first of all to discuss in a little more detail the nature of these radiations, and then to inquire as to the machinery by which the atom sends them out.

To examine the different wave-lengths which a source of light is emitting we have to resort to an instrument. When a chord is struck on a piano, a trained musical ear can tell at once what separate notes are in the chord, but when we are dealing with a light that contains several different distinct wave-lengths, say, a certain definite green light, a certain definite yellow light, and a certain definite red light, each of a given wave-length (a chord of colour, we may call it), no eye can say what these different colours are which exist together in the light. For instance, a white light can be made by mixing three different coloured lights in due proportion, which is to the eye indistinguishable from a white light made by mixing four different coloured lights, or by mixing all the different colours in the right proportions. The way to analyse a light, as it is called, is to use an instrument which separates out the different colours and sorts each into a different place. To get a rough illustration of what is meant, suppose the tickets to the different parts of a theatre were printed in different colours, as red for the pit, orange for the stalls, blue for the dress-circle, and so on. Outside the theatre we have a mixed crowd passing in, corresponding to the beam of mixed light, but inside the various colours are sorted out, and we know by the position in which people sit down what colour their tickets were. A sorting-out instrument for light is called a spectroscope, or, if it is suitable for

photographic recording, a spectograph. The light which enters is spread out into a band, in which each wave-length has its own position, and even a colour-blind man could tell the colours present in the light by the places in which light appears.

The spectroscope is much more sensitive than any eye to differences of shade. Lights of several near wave-lengths all appear to the eye to be the same colour, say, red, even when they have each been put into its proper place. The fact that they fall into different places near one another tells us, however, that the wave-lengths are actually different. If all kinds of light are present (all shades of colour, that is), the spectroscope shows us a continuous band of colour, ranging from red, through orange, yellow, green, blue, and indigo, to violet. There are no gaps in the band. Most people know that sun-light is spread out into such a continuous band (except for certain narrow black lines which need not trouble us here, great as is their importance for certain considerations) by a prism. This was Newton's famous experiment, which led to the discovery that the white light of the sun contains the various colours. The band is known as a spectrum. A continuous spectrum corresponds in music to all the notes being sounded at once: not to a piano having all its notes depressed at once, for the notes in a piano have intervals, tones and semitones, between them, but rather to a violin string being bowed while the finger is slid along the string, without a break, producing a whole range of tones blending into one another. Some spectrographs contain prisms to split up the light; others make use of other devices.

Suppose, however, that we examine, not the light from a glowing solid, but from a glowing gas, say, from one of those tubes filled with the gas neon which give a reddish glow when an electric current is passed through them, and which are so much used for advertising signs at night. We no longer find a continuous band, but certain bright lines separated by dark gaps. The dark gaps mean that the light passing into the spectroscope

from the tube contains no wave-lengths which belong to the places where there is darkness: the light contains, rather, only certain definite wave-lengths corresponding to the positions of the bright lines. We may see red lines, and blue lines, but the exact position of the lines tells us the exact wave-length, while the colour of the lines only tells us roughly in what region of wave-lengths the lines lie. The fact that we see *lines* is due to the fact that the light enters the instrument through a narrow slit: if it entered through a round hole we should see little discs of different coloured light, separated by darkness. The use of a slit is clearly better for accurate measurement, and prevents overlapping. A spectrum which consists of bright lines with darkness between them is called a line spectrum, and clearly corresponds to a chord of colour, in which certain definite notes—wave-lengths—alone are present. Not only visible light, but also infra-red and ultra-violet lines can be measured with the spectroscope: the former are detected by a delicate electrical instrument which measures the heat they produce, while the latter affect a photographic plate. Most modern investigations of spectra are made by photography: the spectrum appears as lines in the photographic plate, and the measurement of the position of these lines gives their wave-length.

Hot solids give a continuous spectrum. In a solid all the atoms are very near to one another, and are always influencing one another—*i.e.*, preventing one another from singing clearly the notes which they naturally want to, as it were. In a gas, especially a gas at low pressure, the atoms are far apart, and, except for occasional collisions, can behave as if they were alone. Clearly, then, if we want to study atoms we should examine the line spectrum of a gas.

The atoms can be made to give out light in various ways. We can shut up the gas in a tube, and pass an electric current through it. We can produce an electric spark or an electric arc. Some of the material of the conductors between which the arc or spark passes is

vaporised, or turned into gas, by the intense heat, and we get the line spectrum of the kind of atoms in question. We can also vaporise metals in flames, and get their spectra in this way. For instance, if a little common salt is brought on a clean platinum wire into a colourless gas flame, such as burns on a gas stove, the flame turns yellow, owing to the fact that the sodium atoms in the salt are giving out a line spectrum, in which the strong visible line is a yellow line. Different ways of stirring up the atom can make it give different spectra, but, in general, not more than two different spectra. We can roughly illustrate this by pointing out that an organ pipe will give a different note according as to whether it is blown violently or softly. The point which must be grasped is, that if we knock the atoms of a gas about by electrical means, or by heat, we can make them utter characteristic shouts of light, as it were, which give us a definite information as to the kind of things they are.

We can make our problem clearer by considering the atom as a musical instrument, say, a piano, draped round with curtains so as to be invisible. We must suppose ourselves to be in the position of a man who has no idea what a piano is like, and who cannot raise the curtains. He can fire bullets through the curtains, and may judge from the fact that they are deflected that within the curtains is something solid. This corresponds roughly to the experiments with alpha particles which reveal the nuclear structure. Occasionally he may knock off a bit of the piano, which is thrown through the curtains. This corresponds roughly to the way in which bits—protons—are knocked off the nucleus. Further, he can knock the piano about by blowing up part of the floor, throwing bricks at it, or even throwing another piano at it, and judge from the noise produced that the piano contains wires strung in certain ways. This corresponds to our experiments on spectra. The idea which the investigator employing these means may form of the piano may not be quite right, but he might

find out that it contains wood, ivory, and wires, and if he was clever, that striking the ivory causes a wire to sound. The illustration is, of course, only very rough, as all such illustrations must be, but it may give some conception of the nature of the problem, and its difficulty.

Before considering how the visible and ultra-violet lines are produced, we must mention that the X-radiations can also be split up into a spectrum, by the use of crystals disposed in certain ways. This was first demonstrated by the German physicist Laue, who was awarded a Nobel prize in 1914, and the methods turned to magnificent account by Sir William Bragg, and his son, W. L. Bragg, who obtained a Nobel prize jointly in 1915. The X-ray spectrum of a given kind of atom consists of certain distinct wave-lengths, or X-ray lines. We know that X-rays are produced by letting the cathode rays, which are very swift electrons, fall on a solid, which in the ordinary X-ray tubes is a lump of metal. The X-ray spectrum produced will depend upon the kind of metal employed. The swift electrons pass right through the atoms, as we have learnt, so that when we produce X-rays we are not just banging about the outsides of the atoms, but stirring up their insides, near the nucleus. Since only the outside electrons of an atom are disturbed by the proximity of another atom, or by chemical combination, solids give the same X-ray line spectrum as the same element in gaseous form, and the X-ray spectrum is not affected, like the optical spectrum, by chemical combination.

The same atom, then, can give out one or more optical spectra, each consisting of a different arrangement of lines, or an X-ray spectrum, the particular radiations which it emits being decided by the way in which we knock it about. The comparatively mild disturbance produced by the flame or the electric arc gives one type of optical spectrum: the more violent disturbance produced by the electric spark gives a different arrangement of lines, but still an optical spectrum: the keen thrusts of the swift electrons into the interior of the atom pro-

duces an X-ray spectrum. We can now turn to the problem of how a given kind of atom sings, as it were, two characteristic songs in the bass, and one in a high soprano.

We know that the atom consists of a nucleus, round which electrons run their courses. We can divide these electrons into groups, of which we can say that, speaking roughly for general purposes, one group consists of electrons whose paths lie comparatively near the nucleus, a second group of electrons whose paths are somewhat farther from the nucleus, and so on, until we come to the outside group, the number of groups depending on the number of electrons in the atom. The heavy atoms, with the most electrons, have the largest number of groups. Now it is an essential feature of the modern theory of the atom that each electron has a definite orbit, to which it sticks unless it is subjected to particularly rough treatment. Let us consider first the outside electrons. It might be supposed that if an outside electron were disturbed by a knock of any kind, it might leave its orbit, and stumble into one very near it. This, however, we find not to be the case. If it is worried, it either takes no notice or else leaves its orbit altogether, and goes to quite a different one a good deal outside the atom. It has a certain choice of orbits to which to go, but it has not a choice of all the orbits which are mechanically possible. We may consider a ball lying at the bottom of a flight of steps. If it is thrown from its position, it may settle on any one of the steps, but cannot decide on a position between the steps. Thus it may, if the steps are one foot high, be thrown into a position one, two, three, or more exact feet from the ground; but it cannot be placed one foot ten inches from the ground, in whatever way we throw it, although there is no law in nature that says a ball may not, in certain circumstances, be placed one foot ten inches from the ground. Similarly, we cannot throw the outside electron into any orbit we like, but only into certain orbits determined by mathematical conditions. When

we throw the electron into such an orbit the energy of the atom is different from its normal value, and we can express what we have said by saying that the atom can exist in certain so-called stationary states, of fixed energies, but cannot exist in states of intermediate energies. Our ball cannot hang in the air. The term "stationary" does not refer to the electron, which is moving, but to the fact that the state is a steady one, in which an atom can exist for a finite time.

Another way of illustrating this fact that an atom can exist in certain stationary states is to suppose a circular board prepared so that the surface slopes gently from the centre, and to have shallow circular grooves, surrounding the centre, cut in it. A ball will then be able to execute certain circular motions—namely, those for which grooves are provided, but will not be able to run round in any intermediate position. The space round the nucleus behaves as if there were grooves in space in which the electrons can run, so that if it be taken out of one groove it has to settle down in another. Why the atom has these stationary states of energy, and cannot have intermediate states, we do not know, but a large number of recent experiments all confirm us in our belief that it does behave in this way.

Suppose, then, that we hit an atom, either with a swift electron, or with another atom moving at comparatively high speed (such as that possessed by atoms in a hot furnace), or that we expose it to an electromagnetic wave of high frequency, we may shake one of the outside electrons into a new orbit, and the whole atom will at once settle into a state in which it has more energy than it normally has. The atom when in this state is said to be excited: we might more colloquially say that it is wound up. We have put energy into it, and that energy is temporarily stored. The atom, however, will seek an opportunity to return to its normal energy state, and after a short interval will do so. (Alternatively it may pass to a stationary state of less energy which is, however, not the normal state, and afterwards pass to

the normal state—*i.e.*, it may return to the normal state in two jumps, instead of all in one jump.) When the atom does return to its normal state, it gives out energy—namely, the energy which we put in when we excited it. This energy is given out as radiation, and the wave-length of the radiation is determined by the amount of energy given out. We will now briefly consider the law which is obeyed.

When we were discussing the quantum, or atom, of radiant energy, we mentioned that it was obtained by multiplying the frequency by a certain fixed number, called Planck's constant. When the atom changes from one stationary state to another, it gives out one quantum, one unit amount, of radiant energy. According to the atom, and to the particular stationary state from which the atom passes to some other stationary state, the amount of energy given out may have very different values, so that, if in all cases it is one quantum, the frequency must also have different values. We may write:

> Energy in higher stationary state minus energy in lower stationary state equals Planck's constant multiplied by frequency.

Planck's constant is known: it is a number fixed once for all, like the velocity of light. Therefore, if we know the energy of the atom in the initial and in the final stationary state, we can very easily find the frequency of the radiation given out. The frequency tells us the wave-length. For the frequency is the number of complete waves given out in one second, so that the frequency multiplied by the wave-length must be the distance travelled by the waves in one second—*i.e.*, the velocity of light, which we know. Hence, if the atom is put in a stationary state which has a great deal of energy, and passes to a stationary state which has little energy, it gives out a high frequency radiation—that is, a radiation of short wave-lengths. Conversely, if it changes but

little in energy, the radiation given out has a long wave-length.

There are various types or orbits permitted, governed by certain mathematical rules which have been worked out for what is, in a sense, a new astronomy—namely, the astronomy of the infinitely little. In the case of the astronomy of the heavenly bodies, we can observe the planets directly, map their motions, and work out a dynamical theory, based on Newton's laws, which enables us to account for their behaviour, and predict their future motions. In the case of the astronomy of the atom, where we are studying the motions of electrons round the nuclear sun, we cannot use the microscope to take the place of the telescope, for the planetary system in question is much too small for the microscope to be any good. Instead, we observe the radiations. A given sort of atom, say, the sodium atom, gives out certain definite wave-lengths only, each one corresponding to a line in the spectrum which characterises sodium, and these waves lengths can be sorted out and arranged in certain series. From the general laws which we have just mentioned the energies of the atom in its different stationary states can be worked out, and from these stationary states different groups of orbits can be deduced. The evidence for the electron orbits is all indirect, but the hypothesis that such orbits exist has introduced a striking simplification into the study of spectra. It has helped us to understand the very complicated schemes of wave-lengths which one kind of atom can emit. Of course, what we observe is the result of millions of millions of atoms undergoing changes. Each atom only gives out one wave-length at a time; but at one time it gives out one wave-length, at another time, by a different permitted change, another wave-length, so that when we observe the radiation from the whole gas we get a sample of every possible radiation which the atom can produce under the given conditions.

This conception of the way in which light is emitted

is known as the quantum theory of spectra, and was first put forward by Professor Bohr, the Danish physicist, who was awarded a Nobel prize in 1922. It is all very mysterious, even to the experts. No one knows why the atom exists in these states separated by finite steps of energy—that is, why it is wound up as if controlled by a toothed wheel and ratchet rather than as if controlled by some kind of friction grip, which would stop it at any stage. No one knows why the radiant energy is given out in quanta, whose frequency is determined by the energy. We only know that all the evidence indicates that things are so. The radiant energy is given out in jerks, and not in a steady supply. The atomic, or granular, nature of things seems to prevail, as against the non-atomic, or continuous, nature, wherever we turn in our quest for fundamental facts.

If an atom be struck hard enough by an electron, it may lose one of its own electrons completely, and so acquire a positive charge as a whole. After existing for a time as a structure which is short of one electron, it may capture some electron which happens to come near, for in a gas which is sending out light there are always plenty of electrons about. The electron will go to one of the selected orbits, and the atom will give out a radiation of wave-length fixed by the change of energy. But it may happen that before the atom has regained the electron which it lost, a second electron is knocked from its normal orbit into another permitted orbit, and that later the two missing electrons are replaced, either one by one, or occasionally, both at once. An atom which has already lost one electron has quite a different series of possible states of stationary energy from an atom which has all its electrons. This accounts for the fact that one kind of atom may give two different spectra, or, as we have put it, can sing two different songs. It is a pretty experiment to pass a mild electric discharge through a gas in a tube, and produce a light of one colour, and then by increasing the violence of the discharge, produce a light of another colour. Of course, in

both cases the light consists of a whole range of different colours mixed together. We have what we have called two different chords of colour.

So far we have spoken of hitting the atom hard enough to displace one or two outside electrons. Suppose, however, we bombard the atom with very swift electrons, as we do in an X-ray tube, where we use large electric forces (very high potentials) to hurl the electrons against the metal lump which is called the anti-cathode. The shock is then violent enough to throw an inside electron out of the atom, which requires a comparatively large amount of energy. An orbit which is possible is then left vacant in the interior of the atom: the atom is in an excited state. Now this orbit can be filled by an electron passing to it from one of the other occupied orbits in the interior of the atom. When this change takes place there is a large change in the energy of the atom, and we have a radiation of very high frequency produced—namely, a penetrating radiation which we call an X-ray. Of course, the orbit vacated by the electron is subsequently filled by an electron from another orbit, until finally an electron from outside the atom comes in to complete the structure again. We thus have X-ray lines produced. The frequency of the radiation depends on the orbits between which the electron is interchanged.

We have, then, to think of an atom in the following way. There is a central nucleus, and round this are certain possible orbits marked out for the electrons. We can, if we like, imagine the electrons as beads running on wires: in that case there will be a large number of separate wires bent into curves surrounding the nucleus. All the wires nearest the nucleus will have electrons running on them, but no electron can run a course in the space between the wires. When we disturb the atom by a strong enough electric shock, one of the outside electrons will leave its wire, and pass to one of the unoccupied wires further out, and run on it. We must suppose that this takes place very quickly in a way not

understood, so that just before the shock we have one arrangement, just after the shock the other arrangement. Later, the electron goes back in a flash to an unoccupied wire nearer the atom. At the same time a little parcel of radiant energy is sent out, of a wave-length which depends upon the two wires concerned in the charge. If we hit the atom still harder, one of the inside electrons leaves its wire. It cannot pass to one of the near wires, since they each have an electron already, but will pass to an unoccupied wire just as the outside electron did. Some other electron will then leave its wire, and pass to the unoccupied wire, and we have an X-ray. The place of the last electron is taken by another electron, and we have another X-ray, of different frequency, and so on, until the atom is in its normal state again. Speaking very roughly, we may say that the electrons trace out certain prescribed patterns, and that when the atom passes from one pattern to another, radiation of some kind is given out.

An atom is, then, a minute broadcasting station, and to each kind of atom certain wave-lengths are allotted. Thus Europe, whose broadcasting stations, taken all together, would give a certain selection of wave-lengths, might be fancifully supposed to represent an atom with a given spectrum. America, which sends out a different sea of wave-lengths, would represent another kind of atom, with a different spectrum. By studying the wave-lengths an expert would tell us the kind of electrical system which each continent contains, and similarly by studying the wave-lengths, the physicist tells us the kind of electrical system which each atom contains. In the case of both broadcasting station and atom, everything reduces to a motion of electricity.

CHAPTER VII

ATOMS AND ENERGY

Energy is the capability to do work, and at the basis of our whole modern industry is a search for convenient sources of energy. Nature offers us certain obvious drivers of our machines, which have been used for centuries, and are being exploited more scientifically to-day. The winds and waterfalls consist of matter which nature has put in motion for us, and the windmill and the water-wheel were early invented to turn part of this energy of motion to the working of machines for grinding corn and performing other mechanical tasks. In these cases we do not have to consider atomic processes: the masses move as a whole, and whether the air and the water consist of atoms or not is indifferent for the purpose in hand.

The other great source of energy which we employ to-day is combustion. In the steam-engine we burn coal or oil, producing heat, which is a form of energy, and it is the task of the engineer to convert this heat energy into work, in which task he is guided by the science of thermodynamics, which we have not space to discuss. In internal combustion engines we likewise burn fuel, petrol or oil, although under somewhat different conditions, for the combustion takes place in the cylinder, and not under a separate boiler, and once more thermodynamical considerations govern the design of the machine which is to convert heat energy into ordered mechanical motion. The ultimate scientific question is, however, as to how this heat energy is liberated by combustion, and here we have an atomic question. The law of the conservation of energy tells us that energy cannot be produced, but only converted from one form to another. In the case of the water-turbine, part of the energy of motion of the water is converted into the

energy which the machine applies to its task: the water enters with a high velocity, and is discharged with a low velocity. In the case of combustion, the products of combustion, which are the gases which issue from the machine (and, in the case of the steam-engine, the solid ashes which remain behind), must contain less energy than the original matter which takes part in the combustion—namely, the fuel and the air of the atmosphere. The vapour and air enter the internal combustion engine, and different gaseous substances are discharged through the exhaust. We have to inquire what the atomic theory tells us of the transformation which has taken place.

The energy of an atom depends, as we have seen, on the particular arrangement of the electrons in orbits. If we can modify the orbits of the atom, we change the energy. Now, when chemical combination takes place between two single atoms, to take the simplest case, the orbits of the outside electrons of each atom must be modified in such a way that the two atoms no longer have an independent existence, but are bound together and move as a whole. The atoms are held by electric forces, but exactly how we do not yet know. In many cases the first stage in chemical combination is that one atom gives an electron to the other atom, so that we have two systems, one of which has an electron above the normal number, and the other an electron less than the normal number. One atom will have a positive charge, the other a negative charge, and they will then attract one another. We cannot yet calculate what will be the orbits of the outside electrons in the molecule formed, and so we cannot calculate for the atomic structure what will be the change in energy when two atoms of given kinds combine, but we can easily understand that there will be a change in energy. This intrinsic or internal energy of the molecule is in general less than that of the separate atoms. The balance of energy appears as the energy of motion of the molecule as a whole. Further, if two molecules interact—that

is, if they reshare the atoms of which they are formed, energy changes take place: the internal energy of the molecules which result from the restoring is not the same as that of the original molecules. In all combustions the internal energy of the molecules which are the products of combustion is less than that of the molecules existing before the combination takes place. To make the total energy before combination equal to the total energy after combination, the molecules formed must rush about more vigorously—that is, must have added energy of motion. This is only another way of saying that the products of combination are hot. We have transformed part of the energy which existed inside the atoms of the molecule into energy of the molecules, which can be detected outside by the increased vigour with which they bang against other molecules. It is as if two heads of businesses went into partnership, cut down the internal running expenses, and put the money so saved into increased activity of their external operations.

In every combination, then, we are, in a sense, using atomic energy, by modifying the energy of the outside electron, and then turning the balance into heat, which is a form of energy easily converted into work. We are also, in most cases, at any rate, breaking atoms, in that in most combustions some of the atoms have to give up an electron. In any case it is quite easy to break an atom, in the sense of removing an electron, as we have seen in discussing the radiations from atoms; in every tube containing glowing gas millions and millions of atoms are having their outside electrons chipped from them, only to have them replaced a little later.

In a sense, then, the utilisation of atomic energy, and the breaking of atoms, is a very familiar process, which is going on all round us. The energy with which we are dealing, however, is that of the outermost electron, which, as we know, is comparatively small, and the electrons which we thus remove are outside electrons which are comparatively loosely attached. Also, we have done the atom no permanent harm: if we separate them

again from the molecule each will regain its old form, by taking up or giving up an electron, or electrons, and we shall have the old energy. To effect this separation, we should, of course, have to put energy into the system in some form or other, but the fact remains that atoms whose outsides are chipped are easily repaired. In a luminous gas they repair themselves.

We know, however, that the atom contains stores of energy which are vastly greater than those with which we tamper in the process of combustion. The nucleus of the atom is itself, in a manner of speaking, a minute molecule within the atom, for it is composed of protons and electrons which are tightly bound together in some sort of way similar to that in which atoms are bound together in molecules. The enormous energy which must be stored in the nucleus is clearly shown by the energy, prodigious when the minute size is considered, with which alpha particles are shot out by radio-active atoms. These alpha particles are fragments of the nucleus; their mass is four times that of a hydrogen atom, and their positive charge twice that on an electron, as explained in Chapter V. So great is the energy given out by the disintegrating nuclei that a volume of the radio-active gas called radium emanation gives out in the course of its transformation six million times as much heat as is given out by the same volume of oxygen and hydrogen burning together, and everyone knows the intense heat of the oxy-hydrogen blowpipe flame. All this energy is given out by the nucleus becoming a simpler nucleus, containing less energy, and flinging off alpha particles (and in some transformations electrons and gamma radiations) in the course of the process, the particles flung off being endowed with the balance of energy.

Radium and other radio-active substances disintegrate spontaneously, a certain fraction of the atoms present undergoing a nuclear change in a fixed unit of time. For some elements the disintegration takes place very rapidly, half the atoms undergoing change in a small

fraction of a second; for others the transformation takes place very slowly, the corresponding time being thousands of years. It is usual to speak of radio-active decay, and just as some substances decay—in the ordinary sense of the word—quickly and others slowly, so do radio-active substances. There is, however, an essential difference in the two kinds of decay. Ordinary decay, as of a piece of meat, is a chemical change, and we can hurry it up or arrest it by ordinary laboratory processes. It is an affair of outside atomic electrons, which are under our control. Radio-active decay, however, is spontaneous, and quite beyond our control. We cannot make it start in atoms which are not naturally radio-active, nor can we stop it in atoms which are naturally radio-active. Further, we cannot even make it occur faster or slower by any agency at our disposal. It is an affair of the nucleus, and the nucleus is so well protected, and deals in such large amounts of energy, that all our heatings and pressures are like trying to dam a waterfall with straws.

In radio-active changes, the element actually changes its nature, for the charge on the nucleus changes, and that, as we have seen, governs the electron planetary system. We have the true transformation of the elements, of which the alchemists dreamt, going on by itself. It is not a transformation of base metals to precious metals—in fact, the very precious radium slowly changes, by successive stages, to ordinary lead, which is the end of the journey. In the course of the transformation there is a great release of energy. If we could only provoke deliberately a transformation of the elements, and make lead, say, change to a lighter element, for instance, to mercury or gold, we should release nuclear energy, which would be liberated in such quantities that we should not trouble much about the value of the metal produced. A given weight of lead changing to gold would, we may conjecture, from the behaviour of the radio-active elements, produce somewhere about a hundred million times as much heat as the same weight of

coal burning, so that a ton of coal could be replaced by a fraction of a grain of lead, whose value when turned to gold would be about a farthing. If we were able to release and control nuclear energy we should not need to worry about coal or oil as a source of energy.

Are there any indications that we can in any way get at the nucleus? As we have already said, ordinary laboratory methods, such as high temperature and pressure, are powerless. The very swift projectiles, electrons and alpha particles, which the radio-active substances themselves emit furnish us, however, with a very powerful weapon. We know that they can penetrate right through the outer electronic structure of the atom, and pass near to the nucleus. Of the two, the alpha particles are the slower, but, on account of their much greater mass, they have the greater energy, and can smash their way right up to the nucleus. Sir Ernest Rutherford was the first to show how information as to the nucleus could be won by bombarding atoms with the alpha particles from elements of the radium family, and most of the reliable work on the subject has been carried out in the Cavendish Laboratory at Cambridge, either by him, or under his direction. By studying the scintillations produced on a phosphorescent screen by the flying alpha particles and by the products of their collisions with nuclei, he has been able to show that, when an alpha particle hits a nucleus fair and square, it can knock a proton out of it. This is a true breaking of the atom, for the nucleus is definitely changed, and a fresh type of atom produced. He has also, however, been able to show that with certain elements, notably aluminium, the proton comes out with an energy greater than that of the alpha particle which caused its release. In this case, then, we are actually releasing part of the energy stored in the nucleus. We have not a case similar to that of a ball knocking a skittle out from the circle, where the energy with which the skittle travels must always be less than that of the ball, but rather a case of some kind of trigger action, as if a ball were to hit

may be neglected. Shall we ever be able to release the nuclear energy in appreciable quantities, and if we can release it, shall we be able to control it? At the present stage an answer must be sought from the romancers rather than from men of science. Whether the source of energy, if found, will lead to new happiness, or to vast increases in population followed by ruthless wars, is a question to which the answer must at present be dictated by temperament rather than by reason.

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